

## Hazard Profile – Tsunami

### Summary

- The hazard – A tsunami is a train of waves typically generated during an earthquake by sudden displacement of the sea floor or lake bed. As demonstrated on Indian Ocean shores in December 2004, tsunamis can cause vast death and destruction without regard for political boundaries. They are particularly dangerous close to their sources, where the first wave in the tsunami train can arrive less than an hour after the tsunami begins and where the earthquake has already created havoc.
- Previous occurrences – Washington State has a long history of tsunamis from sources near and far. The largest of the nearby sources, the Cascadia Subduction Zone, produced its most recent great tsunami in 1700. The region's backyard tsunamis also include a Puget Sound tsunami from the Seattle Fault between 900AD and 930AD, a Tacoma Narrows tsunami from a landslide in 1949, a fatal wave from a rockfall into the Columbia River in 1965, and a great slosh from Spirit Lake during the 1980 eruption of Mount St. Helens. The State's greatest Pacific Ocean tsunamis in recent memory came from Chile in 1960 and Alaska in 1964.
- Probability of future events – Tsunamis generated elsewhere on the Pacific Rim are the ones that strike Washington most often. The Washington portion of the Cascadia Subduction Zone produces a great earthquake (magnitude 8 or 9) and associated tsunami often enough for the next of these to have a one-in-ten chance, or better, of occurring in the next fifty years. The frequency of tsunamis from inland sources has not been determined.
- Jurisdictions at greatest risk – Communities along the Pacific Coast and Strait of Juan de Fuca, including a number of coastal Indian tribes, are at greatest risk. In a Cascadia Subduction Zone earthquake, the level of the coast could fall or subside six feet, and tsunami waves could reach 30 feet, overtopping several low-lying coastal communities. The at-risk population from a Cascadia-related tsunami is approximately 43,000 residents and 25,000 employees (Wood and Soulard, 2008; based on 2000 U.S. Census population counts) on the outer coast, excluding tourists and transient populations that could increase the number significantly. In a 2008 study of community exposure on the open-ocean coast of Washington to Cascadia-related tsunamis, the City of Aberdeen had the highest number of residents, employees, dependent-population facilities, public venues, and total parcel value in the tsunami-hazard zone (Wood and Soulard, 2008).

Global Perspective – In its earthquake and tsunami potential, the Pacific Northwest rivals the source areas of the greatest tsunamis of the last 100 years: Chile, Alaska, and Sumatra. Like all these areas, Cascadia has a track record of generating ocean-wide tsunamis from earthquakes as large as magnitude 9.

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### Introduction<sup>1, 2, 3</sup>

Tsunamis are trains of waves that threaten people and property along shorelines of the Pacific Coast, Strait of Juan de Fuca, Puget Sound, and large lakes. Sudden raising or lowering of the sea floor or a lake bed during an earthquake typically generates a tsunami, although landslides and underwater volcanic eruptions also can generate them.

Only as a tsunami approaches land does it become a hazard. In shallow water, it gains height as its waves slow and compress. Tsunamis can resemble a series of quickly rising tides, and they can withdraw with currents much like those of a river; they can also form breaking waves but these are less common than tsunami icons suggest. Swift currents commonly cause most of the damage from tsunamis. A Pacific Ocean tsunami can affect the entire Pacific basin, while a tsunami generated in inland waters can affect many miles of shoreline.

Tsunamis typically cause the most severe damage and casualties near their source. There, waves are highest because they have not yet lost much energy. The nearby coastal population, already reeling from the effects of an earthquake, may have little chance to flee before the tsunami arrives. Persons caught in the path of a tsunami often have little chance to survive; debris may crush them, or they may drown. Children and the elderly are particularly at risk, as they have less mobility, strength, and endurance.

**Table 1. Recent Subduction Zone Earthquakes and Tsunamis Worldwide, 1946 – January 2010**

Date	Origin	Effects	Casualties
April 1, 1946	Aleutian Islands	This tsunami destroyed the Scotch Cap Lighthouse on Unimak Island, killing five, and killing 173 in Hawaii; led to creation of The Pacific Tsunami Warning Center	178 dead in Alaska and Hawaii
May 22, 1960 <sup>4</sup>	South-Central Chile EQ Magnitude 9.5	Largest earthquake in world. Damage to Chile, Hawaii (61 tsunami deaths), and Japan (118 tsunami deaths).	4,000-5,000 dead; 3,000 homeless; 2 million injured.
March 27, 1964 <sup>5</sup>	Prince William Sound, Alaska EQ Magnitude 9.2	Second-largest earthquake in 20th century. Shaking lasted 3 minutes. Severe damage to south coast of Alaska. Wave height at Valdez Inlet estimated at 220 feet. Tsunami deaths in AK, OR, Crescent City, CA.	125 dead (tsunami 110, EQ 15)
Aug. 23, 1976 <sup>6</sup>	Celebes Sea EQ Magnitude 7.9	Southwest Philippines struck, devastating Alicia, Pagadian, Cotabato and Davao.	8,000 dead
July 17, 1998 <sup>7</sup>	Papua New Guinea EQ Magnitude 7.1	Arop, Warapu, Sissano, and Malol, Papua New Guinea devastated. Wave height estimated at 33 feet.	2,200 dead; 200 missing; 9,500 homeless

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Dec. 26, 2004 <sup>8,9</sup>	Sumatra, Indonesia EQ Magnitude 9.0	Parts of Indonesia, Thailand, Malaysia, India, Sri Lanka, Maldives devastated. Wave heights reached 100 feet. Tsunami measured around the world.	283,000 dead; 14,100 missing; 1.1 million displaced
March 28, 2005 <sup>10</sup>	Sumatra, Indonesia EQ Magnitude 8.7	Parts of Sumatra Island, Indonesia badly damaged. Wave height estimated at 10 feet.	1,400 dead
September 29, 2009 <sup>11</sup>	South Pacific Basin, Samoa EQ Magnitude 8.0	Parts of American Samoa, Western Samoa, and Tonga were severely impacted. Run-up of 56 feet was reported.	160 dead, 7 missing

A tsunami crosses the ocean at jetliner speeds, close to 600 miles per hour. The 1964 tsunami from Alaska's Aleutian Islands took less than five hours to reach Hawaii, where it killed 159 people. Computer simulations show that the January 26, 1700 tsunami from the Cascadia Subduction Zone along the Pacific Coast of Washington took about 10 hours to reach Japan, where it caused flooding and damage along 600 miles of the Pacific coast of Honshu.

Tsunami waves in the ocean can continue for hours; later waves can be larger, more deadly, and more damaging. For example, the first wave to strike Crescent City, CA, following the 1964 Alaska earthquake was 9 feet above the tide level; the second was 6 feet above tide; the third was about 11 feet above the tide level; and the fourth, most damaging wave was more than 16 feet above the tide level. The third and fourth waves killed 11 people. Estimates of the damage range from \$47 million to \$97 million (2004 dollars). The same tsunami destroyed property in many areas along the Pacific coast from Alaska to California. In Washington, the largest wave entered Willapa Bay about 12 hours after the first one; the tsunami caused \$640,000 (2004 dollars) in damage (see Table 2, page 5, for wave heights along the Washington coast).

Although the 1964 event was the largest 20th-century tsunami on the Washington coast, the state has its own sources of tsunamis, and these have produced great waves recorded geologically in the last few thousand years.

### Tsunami Threat in Washington<sup>12</sup>

Washington's outer coast faces a dual threat: tsunamis generated by distant sources such as earthquakes in Alaska and Chile, and tsunamis generated directly offshore during earthquakes on the Cascadia Subduction Zone. (For more information on the subduction zone, see the graphic on page 4, and the Earthquake hazard profile).

Off Washington State the Cascadia Subduction Zone has generated magnitude 8 or larger earthquakes at least six times in the past 3,500 years. Each is known or suspected to have set off a tsunami. The most recent occurrence dates to the evening of January 26, 1700. During this earthquake and its predecessors, much of the land on Washington's outer coast subsided, or fell, by about five feet. Such lowering of the land

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makes coastal communities more susceptible to flooding and damage from the ensuing tsunami.

Computer models indicate that a Cascadia-generated tsunami could reach nearly 30 feet in height and affect the entire Washington coast. The first wave would reach coastal communities within 30 minutes after the earthquake, and communities along the Strait of Juan de Fuca in 90 minutes. Tsunamis from great Cascadia earthquakes probably account for several sand sheets on northwestern Whidbey Island and at Discovery Bay in Puget Sound.

The Cascadia Subduction Zone, in its earthquake and tsunami potential, is similar to the Sunda Trench off the coast of Sumatra Island, Indonesia. A graphic that compares those two geologic structures is on page 4.

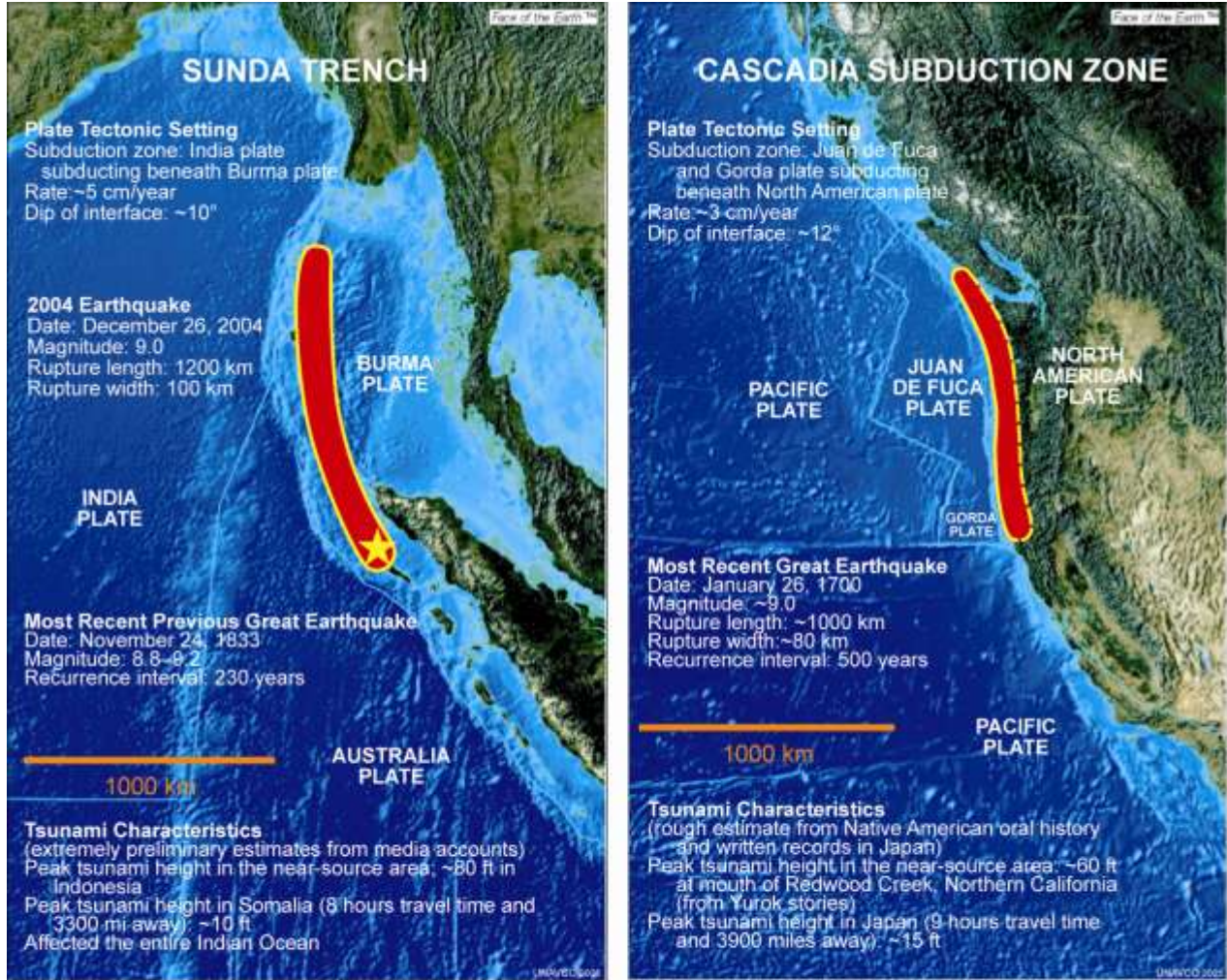
Washington's Puget Sound waters also are subject to tsunamis. An earthquake around A.D. 900-930 on the Seattle Fault caused uplift that triggered a tsunami in central Puget Sound. And, a landslide into the Tacoma Narrows set off a tsunami a few days after the 1949 Olympia earthquake.

### *Probability of Occurrence for Tsunami*

Great earthquakes in the Pacific Ocean generate tsunamis that sweep through the entire Pacific basin occur at a rate of about six every 100 years. In the Cascadia Subduction Zone, scientists currently estimate there is a 10 to 14 percent chance an M9.0 earthquake and associated tsunami will occur in the next 50 years.<sup>13</sup> A specific rate of occurrence has not been calculated for local earthquakes and landslides that generate tsunamis.

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### Comparing the Cascadia Subduction Zone with the Sunda Trench<sup>14</sup>



This graphic, compiled by Lori Dengler, Professor of Geology at Humboldt State University, Arcata, CA, compares the Sunda Trench subduction zone, the location of the December 2004 Indonesia earthquake and tsunami, with the Cascadia Subduction Zone off the Pacific Northwest Coast. The earthquake rupture zones are red with yellow border; the star shows the epicenter of December 2004 earthquake.

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### Examples of Tsunamis on Washington's Pacific Coast<sup>15, 16, 17, 18</sup>

While tsunamis have caused significant damage, deaths and injuries elsewhere in the world, only one significant tsunami struck Washington's Pacific coast in recent history. The 1964 Alaska earthquake generated a tsunami that resulted in more than \$640,000 (in 2004 dollars) in damage. However, geologic investigations indicate that tsunamis have struck the coast a number of times in the last few hundred years.

#### *1700 Cascadia Tsunami*

The most recent Cascadia Subduction Zone earthquake, estimated M9, produced a tsunami on Washington's coast in 1700. The tsunami overran Native American fishing camps and left behind telltale sheets of sand on marshes and in lakes along the southern part of the coast. A sand sheet at Discovery Bay in the eastern Strait of Juan de Fuca also probably resulted from the 1700 tsunami.

Japanese written history pinpoints this event to the evening of January 26, 1700. There, the tsunami began in the middle of the night of January 27-28 Japan time and continued until the following afternoon or evening. Its waves drove villagers to high ground, drowned their paddies and crops, damaged their salt kilns and fishing shacks, entered a government storehouse, and ascended a castle moat. It destroyed dozens of buildings, including 20 houses consumed by a fire that the flooding started or spread. It set in motion a nautical accident that sank tons of rice and killed two sailors. It led samurai to give rice to villagers left hungry and to request lumber for those left homeless. The tsunami left a village headman wondering why no earthquake had warned of its coming.

#### *1960 Chilean Tsunami*

A magnitude 9.5 earthquake along the coast of Chile generated a tsunami that struck the Washington coast at Grays Harbor (small waves), Tokeland (two feet), Ilwaco (two feet), Neah Bay (1.2 feet), and Friday Harbor (0.3 feet). No damage occurred.

#### *1964 Alaskan Tsunami*

The tsunami generated by the March 27, 1964 Alaska earthquake was the largest and best-recorded historical tsunami on the Washington coast. Tsunami wave heights generally were greatest on the south coast and smaller on the north coast; additionally, the tsunami was recorded inland in the Strait of Juan de Fuca (Friday Harbor), Puget Sound (Seattle), and the Columbia River (Vancouver).

Observations were made of the tsunami in Grays Harbor County at Westport, Joe Creek, Pacific Beach, Copalis, Grays Harbor City, and Boone Creek.

Damages included debris deposits throughout the region, minor damage in Ilwaco, damage to two bridges on State Highway 109, a house and smaller buildings being

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lifted off foundations in Pacific Beach (the house was a total loss), and damage to the Highway 101 bridge over the Bone River near Bay Center when the Moore cannery building washed against its pilings.

**Table 2. Recorded Height of Tsunami Waves from 1964 Alaska Earthquake**

Wreck Creek	4.5 meters	Neah Bay	0.7 meters
Seaview	3.8 meters	Taholah	0.7 meters
Moclips	3.4 meters	Hoh River Mouth	0.5 meters
Ocean Shores	2.9 meters	Friday Harbor	0.4 meters
La Push	1.6 meters	Vancouver	0.1 meters
Ilwaco	1.4 meters	Seattle	0.1 meters

Additional information concerning observations from the 1964 tsunami on the Washington coast are highlighted below in an excerpt from the Tsunami Hazard Map of the Southern Washington Coast by Timothy Walsh, et al (2000).<sup>19</sup>



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**Table 1.** Observations of the 1964 tsunami on the Washington coast. Height is height of highest wave; MLW, mean low water; MSL, mean sea level. Estimated damage is in 1964 dollars (from Hogan and others, 1964; Wilson and Torum, 1972; and newspaper accounts)

Location	Map no.	Height (ft) above tide	Height (ft) above MLW	Height (ft) above MSL	Estimated damage	Type of damage	Photo
Coast Guard Station, Cape Disappointment	1	5.7	11.9	8.3		None	
Town of Ilwaco	2	4.5	10.7	7.1		Minor damage	
Town of Seaview	3	12.5	19.5	14.8		None	
Ocean Shores	4	9.7	18.1	13.3		Deposition of debris on streets near Central Motel Office. Debris on streets and yards in vicinity of break in sand dune dike about ¼ mile south of motel	
State Highway 109, Copalis River Bridge	5					Loss of one four-pile timber bent and two timber spans near the bridge center and one piling in a four-pile timber bent.	9-1-A; Fig. 3
Town of Copalis, Copalis River	6				\$5,000	Damage to buildings	
State Hwy 109 at Boone Creek	7				\$5,000	Erosion of 80 ft (24 m) of shoulder and deposition of debris on highway.	8-4-A
Iron Springs Resort	7				\$500	Foundation and water damage to one house and deposition of debris in yard.	
State Highway 109, Joe Creek Bridge	8				\$75,000	Loss of five-pile bent, damage to two pile bents (loss of three pilings), and loss of two 20-ft (6.1-m) reinforced concrete spans.	8-3-A; Fig. 4
Town of Pacific Beach	9	12-14 (est.)			\$12,000	Medium-sized house lifted off the foundation and partly torn apart; total loss. Several sheds moved off foundations. A second building partly damaged. Yards eroded and covered with debris.	8-2-A; Fig. 5
Town of Moclips	10	11.1	19.7	14.9	\$6,000	Damage to ocean side of buildings by floating logs; one building moved off foundation. Timber pile bulkheads and fills extensively damaged. Water over some floors from 6 in. to several feet. Heavy debris scattered over yards.	8-1-A, B,C; Figs. 6,7,8
State Highway 109, Wreck Creek Bridge	11	14.9	23.5	18.83	\$500	Erosion of fill at bridge approach; debris on bridge deck and nearby highway.	7-1-A
Taholah	12	2.4	11.0	6.3	\$1,000	Loss of several skiffs and fish nets in inlet at mouth of Quinalt River.	
Mouth of Hoh River		1.7	10.1	5.6		None	
La Push		5.3	13.7	9.3		Several boats and a floating dock broke loose from moorings.	
U.S. Highway 101, Bone River Bridge	13					Pilings damaged when the Moore cannery building was lifted off its foundation and washed against the south approach of the Highway 101 bridge over the Bone River	
Raymond docks		3.5-4 (est.)				None	



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### *November 2006 Tsunami*

On Nov 15, 2006, a magnitude 8.3 earthquake occurred near the Kuril Islands northeast of Japan. Washington was put into a Tsunami Advisory. A 5 cm tsunami was recorded on the Neah Bay tide gage. However, after the cancellation of the Tsunami Advisory, a train of tsunami waves hit Crescent City, California six hours after the earthquake and destroyed docks, tore about a dozen boats lose from moorings, and sank at least one boat.

**Table 3. Recorded Height of Tsunami Waves  
from 2006 Kuril Island Earthquake**

Location	Wave height
La Push	.52 feet
Neah Bay	.01 feet
Port Angeles	.39 feet
Westport	.16 feet

### **Puget Sound Tsunamis**<sup>20, 21, 22, 23, 24</sup>

#### *A.D. 900-930 Tsunami*

An earthquake between the years 900 and 930 raised shores of central Puget Sound by 20 feet between the Duwamish River and Bremerton. The uplift, by also including the floor of Puget Sound, created a tsunami. In Seattle, the tsunami washed across West Point, where it deposited a sheet of sand. Farther north, it deposited a sand sheet at Cultus Bay on southern Whidbey Island and along tributaries of the Snohomish River between Everett and Marysville. Computer simulations of the tsunami show it reaching heights of 20 feet or more at the Seattle waterfront.

#### *Early 1800s Camano Head Tsunami*

Historical accounts among the Snohomish Indian people describe a landslide at Camano Head that sent a large wave south toward Hat Island. Camano Head is at the south end of Camano Island in Puget Sound. According to tribal accounts, the landslide sounded like thunder, buried a small village and created a large volume of dust. The tsunami washed over the barrier beach at Hat Island, destroying homes or encampments and drowning many people. The accounts make no mention of ground shaking, suggesting that the slide was not associated with a large earthquake.

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### *1891 Puget Sound Tsunami*

Water in Lake Washington and Puget Sound surged onto beaches two feet above the high water mark, rocking vessels that had just pulled away from wharves, and causing an elevator in one building to bump against the side of the shaft. The likely cause of this November 29 event was two earthquake shocks and submarine landslides.

### *1894 Commencement Bay Tsunami*

A submarine landslide in the delta of the Puyallup River in Commencement Bay, Tacoma, caused a tsunami. These events carried away a railroad track and roadway, resulting in two deaths.

### *1949 Puget Sound Tsunami*

A small landslide-generated tsunami struck the Point Defiance shoreline in the Tacoma Narrows on April 16, three days after a M7.1 earthquake weakened the hillside. According to local newspaper reports, an 11 million cubic yard landslide occurred when a 400-foot high cliff gave way and slid into Puget Sound. Water receded 20-25 feet from the normal tide line, and an eight-foot wave rushed back against the beach, smashing boats, docks, a wooden boardwalk, and other waterfront installations in the Salmon Beach area. The slide narrowly missed a row of waterfront homes struck by the tsunami.

## **Inland Tsunamis**

### *Lake Roosevelt Tsunamis*

Landslides into Lake Roosevelt in eastern Washington generated numerous tsunamis from 1944 to 1953 after Grand Coulee Dam created the lake on the Columbia River. Most tsunamis generated large waves (30 to 60 feet in height) that struck the opposite shore of the lake, with some waves observed miles from the source. Two tsunamis caused damage:

- *February 23, 1951* – A 100,000 to 200,000 cubic yard landslide just north of Kettle Falls created a wave that picked up logs at the Harter Lumber Company Mill and flung them through the mill 10 feet above lake level.
- *October 13, 1952* – A landslide 98 miles upstream of Grand Coulee Dam created a wave that broke tugboats and barges loose from their moorings at the Lafferty Transportation Company six miles away. It also swept logs and other debris over a large area above lake level.
- *January 16, 2009*—Another landslide –induced tsunami reached a height of about 30 feet and damaged docks at Breezy Bay, Moccasin Bay, Sunset Point and Arrowhead Point

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### *1965 Puget Island Tsunami*

This tsunami occurred in 1965. A landslide-triggered tsunami overran Puget Island in the Columbia River near Cathlamet. The landslide originated from Bradwood Point on the Oregon side of the River. The wave killed one person.

### *1980 Spirit Lake Tsunami*

The May 18, 1980 eruption of Mount St. Helens caused a massive tsunami in Spirit Lake. The sliding north face of the volcano slammed into the west arm of the lake, raising its surface an estimated 207 feet and sending a tsunami surging around the lake basin as high as 820 feet above the previous lake level. Displaced water rinsed the valley sides clean of timber and sediment, jamming logs and boulders against the landslide debris. In the east arm of Spirit Lake, the tsunami wave reached nearly 740 feet above the old level of the lake, also washing trees off the sides of the valley and into the lake.

### **Seiche**<sup>25, 26, 27</sup>

Seiches are water waves generated in enclosed or partly enclosed bodies of water such as reservoirs, lakes, bays and rivers by the passage of seismic waves (ground shaking) caused by earthquakes. Sedimentary basins beneath the body of water can amplify a seiche. Seismic waves also can amplify water waves by exciting the natural sloshing action in a body of water or focusing water waves onto a section of shoreline.

In a 2003 paper, researchers at the University of Washington and the National Oceanic and Atmospheric Administration indicate that the geology of the sedimentary basin beneath Seattle amplifies seismic waves from large and distant earthquakes, contributing to the damaging effects of water waves in local enclosed bodies of water.

The November 2002 magnitude 7.9 Denali earthquake in Alaska produced water waves damaging about 20 houseboats in Seattle's Lake Union, buckling moorings, and breaking sewer and water lines. Sloshing action was reported in swimming pools, ponds and lakes around Seattle. Newspaper reports indicate water waves from the 1964 M9.2 Alaska earthquake caused similar damage on the lake as well as overtopping the Fairview Hill reservoir and washing gravel into an Aberdeen neighborhood; sloshing wave action also was reported following the 1949 M7.1 Olympia earthquake and the 1965 M6.5 Seattle earthquake.

Researchers believe local amplification of seismic waves could make other urban areas above sedimentary basins in the region particularly vulnerable to seiches or water waves during large earthquakes on the Seattle Fault or the Cascadia Subduction Zone.

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### **Jurisdictions Most Vulnerable to Tsunami** <sup>28, 29</sup>

Areas vulnerable to tsunamis in Washington state include ocean beaches , bay entrances, tidal flats, the banks of tidal rivers, and some inland waters.

Washington began creating tsunami inundation models and maps for its Pacific Coast shoreline in the late 1990s using funds from the National Tsunami Hazard Mitigation Program. To date, tsunami inundation mapping for a Cascadia Subduction Zone earthquake is complete for most shorelines of the Pacific Coast and Strait of Juan de Fuca. Modeling and mapping is complete for an earthquake on the Seattle Fault for Seattle and Tacoma, and on the Tacoma Fault for Tacoma. Modeling for tsunamis caused by surface faults in the Everett area and in Lake Washington is underway or scheduled.

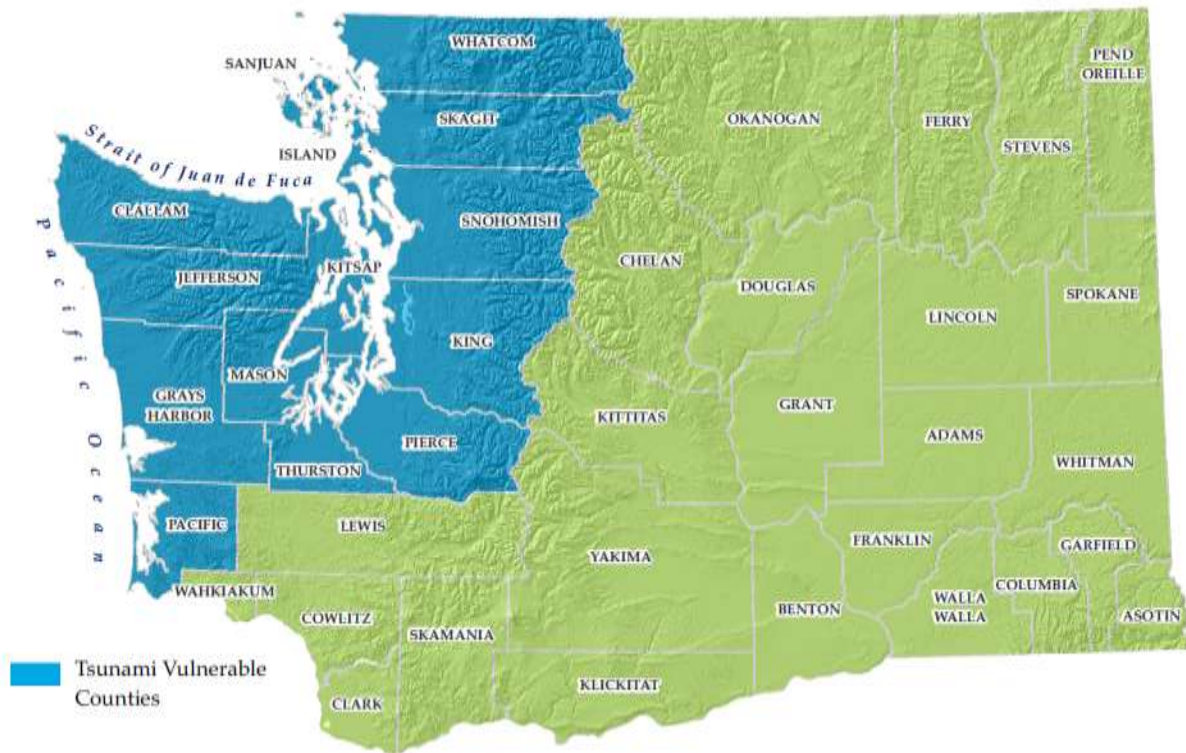
The Washington Department of Natural Resources Division of Geology and Earth Resources prepares tsunami inundation maps from the modeling. Local governments then use inundation maps to develop evacuation maps for their communities.

The state map below highlights the counties considered most at-risk and vulnerable to tsunamis; the latest inundation maps, population estimates and communities considered most at risk are on the pages that follow. A study co-sponsored by the State Emergency Management Division and the U.S. Geological Survey completed in 2008 provides more detailed estimates on population, infrastructure and local economic assets in the Cascadia-related tsunami-hazard zones of Clallam, Jefferson, Grays Harbor and Pacific counties (Wood and Soulard, 2008).

Estimates for state agency facilities located in the tsunami hazard zone were developed using the inundation maps on the following pages.

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### Counties Most At-Risk and Vulnerable to Tsunamis



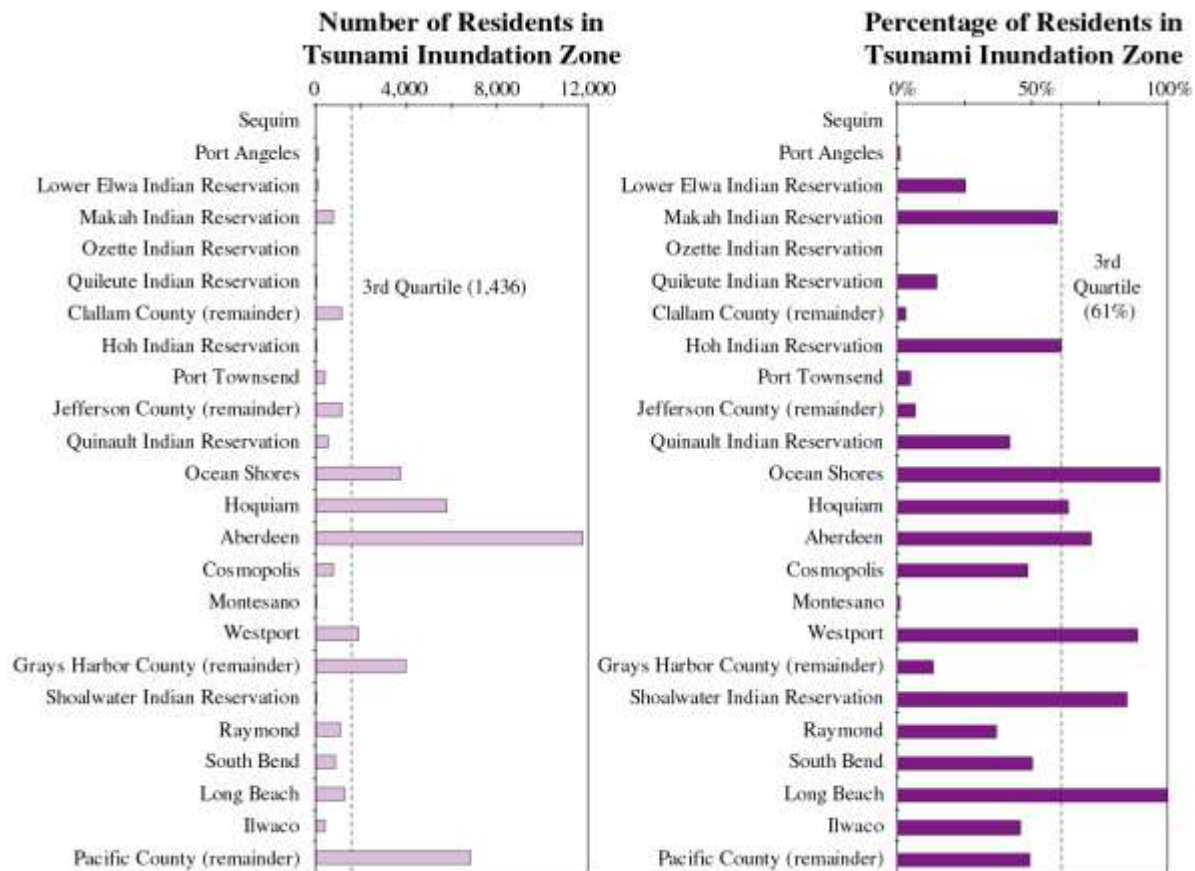
*Pacific Coast, Strait of Juan de Fuca*<sup>30, 31, 32, 33</sup>

The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts models use a M9.1 earthquake on the Cascadia Subduction Zone off the Washington coast as the generator of the tsunami.

The estimated at-risk population in the four counties bordering the outer Pacific Coast is 42,972 residents (based on the 2000 U.S. Census), representing 24% of the total people in these counties (Wood and Soulard, 2008). It does not include at-risk communities on the east end of the Strait of Juan de Fuca such as Bellingham, Anacortes and Mount Vernon, and Island and San Juan counties; their at-risk populations have not been calculated.

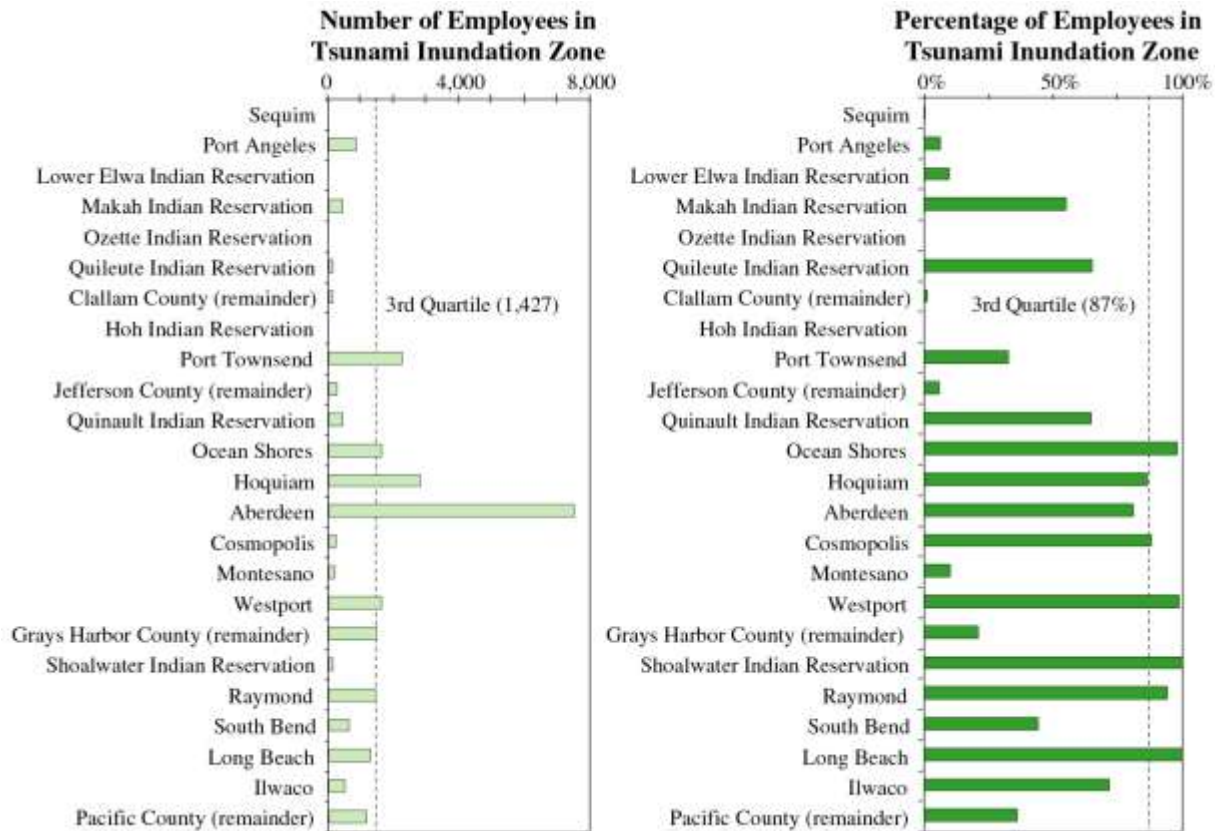
Within the four counties bordering the Pacific Ocean, the City of Aberdeen has the highest number of residents (11,781) in the tsunami-inundation zone. Approximately 13,096 residents in tsunami-prone areas are outside of the 13 incorporated cities and 7 Indian reservations and are primarily in the unincorporated portions of Pacific County (6,823) and Grays Harbor County (3,957). Many communities have low numbers but high percentages of residents in the tsunami-inundation zone, including the Makah Indian Reservation (802 residents, representing 59 percent of the community), the Hoh Indian Reservation (62 residents, 61 percent), South Bend (900 residents, 50 percent), and Long Beach (1,281 residents, 100 percent).

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The tsunami-inundation zone contains 24,934 employees (based on 2007 economic data), representing 33 percent of the employees in the four coastal counties (Wood and Soulard, 2008). Certain communities such as Hoquiam and Aberdeen have high numbers of employees in the tsunami-inundation zone (2,792 and 7,488, respectively) that represent high percentages of their community workforce (86 percent and 81 percent, respectively). Other communities have much lower numbers of employees in the tsunami-inundation zone, including Shoalwater Indian Reservation (138), but these employees represent the entire community workforce.

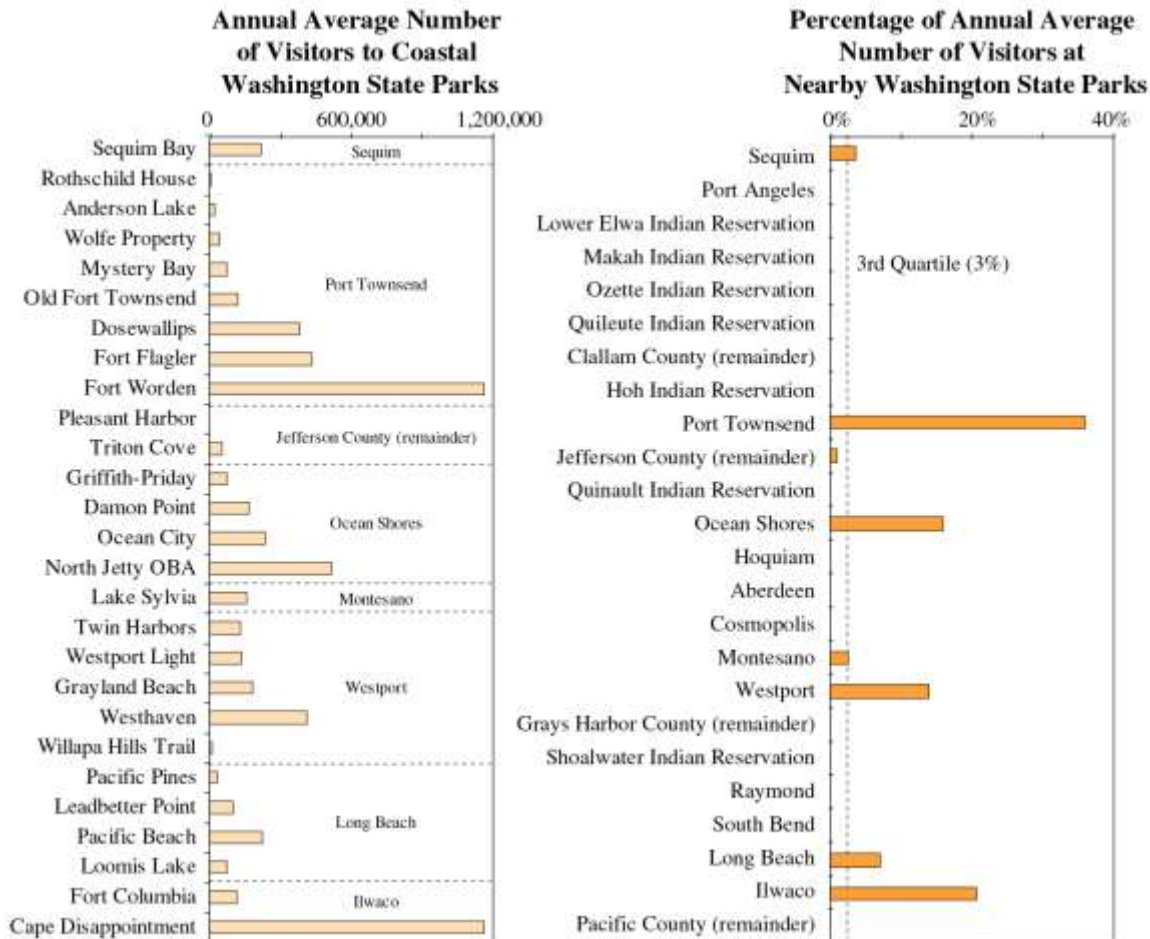


These at-risk population estimates exclude the thousands of tourists that populate at-risk beach areas at various times of the year. Analysis of visitor data from Washington State Parks in Wood and Soulard (2008) suggests that 27 parks in the tsunami-inundation zone of the study area receive a significant amount of day tourists. The highest annual average of day-use visitors for the 27 parks are for Fort Worden (1,164,125 visitors and near Port Townsend) and Cape Disappointment (1,162,447 visitors and near Ilwaco). The sum of annual average visitors to the 27 coastal parks of the Washington State parks selected in Wood and Soulard (2008) is 6,215,569 people (2007 estimates). Assuming an equal distribution of visitors on every day of the year, this equates to 17,029 day-use visitors to these coastal State parks on average every day. In reality, this number is low because attendance is not equally distributed throughout the year; there will be seasonal peaks in park attendance (for example, summer months and holidays). Clustering the number of visitors of coastal parks to



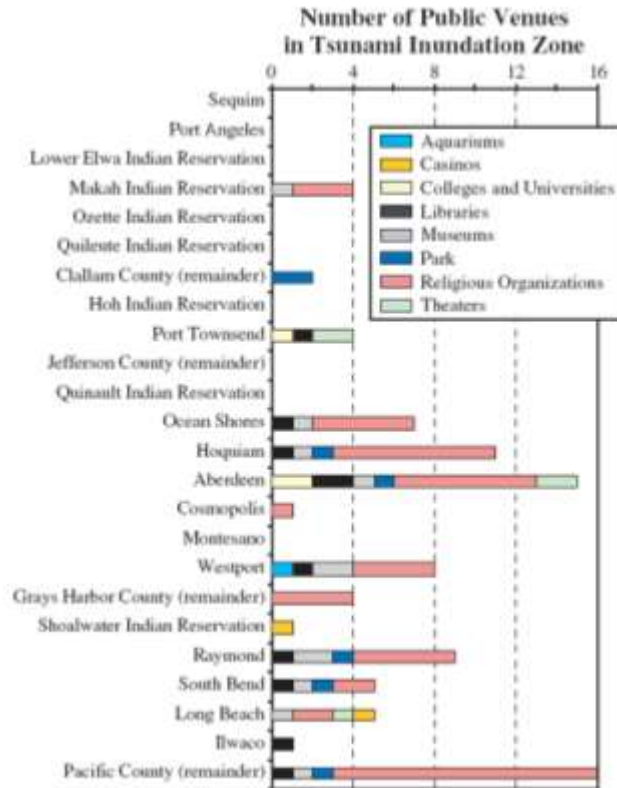
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nearby towns, it is clear that the majority of visitors are going to parks near Port Townsend (36 percent) on the Strait of Juan de Fuca and Hood Canal coasts, followed by parks near Ilwaco (21 percent), Ocean Shores (16 percent), and Westport (14 percent). Therefore, in addition to dealing with residents and employees within the tsunami-inundation zones of their communities, cities like Port Townsend may have significant numbers of tourists that are visiting nearby State Parks when a tsunami occurs

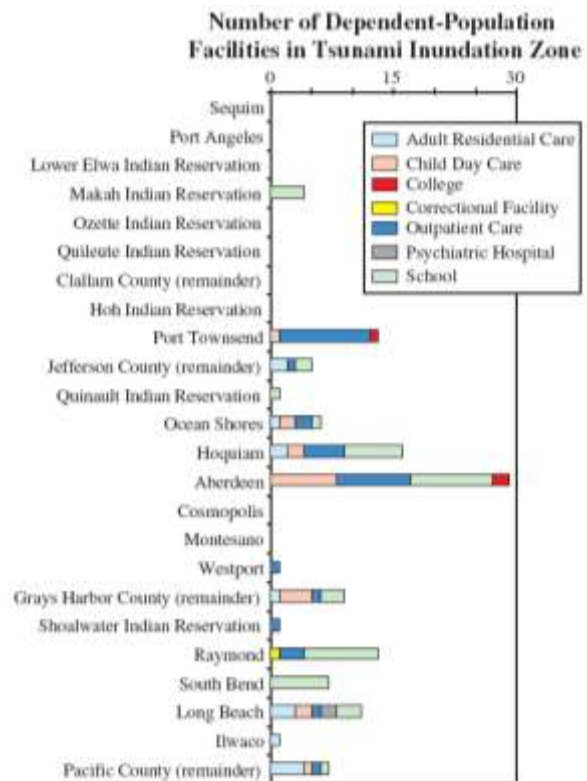


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The tsunami-hazard zone of the four counties bordering the Pacific Ocean also contains several public venues that likely attract high numbers of local populations (Wood and Soulard, 2008). The highest number of public venues in the tsunami-inundation zone are in the unincorporated areas of Pacific County (16 facilities) and the majority of them are religious facilities (for example, churches). The next highest numbers of public venues in the tsunami-inundation zone are in the coastal communities of Grays Harbor County (for example, Aberdeen, Ocean Shores, Hoquiam, and Westport).

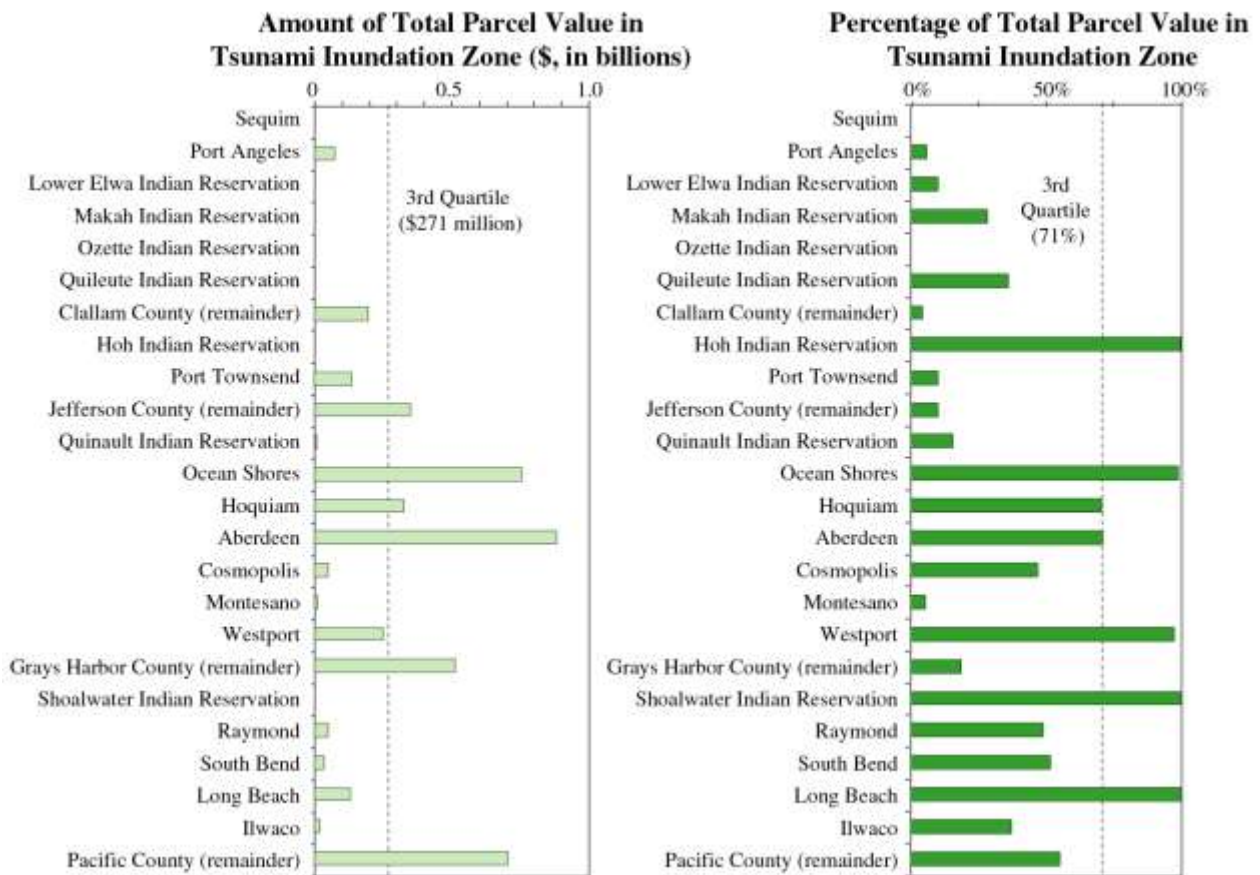


This tsunami-hazard zone also contains several dependent-population facilities that house individuals that would require evacuation assistance in the event of a tsunami warning (Wood and Soulard, 2008). Many of these facilities are in central-coast communities, specifically the cities of Aberdeen and Hoquiam.



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The tsunami-inundation zone of the four counties bordering the Pacific Ocean contains parcel values assessed at approximately \$4.5 billion (2007 U.S. dollars), representing 25 percent of the total parcel values in the four coastal counties (Wood and Soulard, 2008). The highest total exposed tax parcel values for the 20 communities are in Aberdeen (\$887 million) and Ocean Shores (\$759 million), representing 71 percent and 99 percent, respectively, of the total tax base in the communities. The third highest total parcel values is in the unincorporated portion of Pacific County, primarily reflecting the unincorporated town of Ocean Park. Although many communities have relatively low amounts of total parcel value in the tsunami-inundation zones, the exposed parcels represent a high percentage of a community's total assets. Building damages due to CSZ-related tsunamis, as well as from the preceding earthquake, could significantly lower the content value of individual properties, thereby lowering the tax base of a community after a tsunami disaster, and reducing the funds available for long-term recovery.



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A Cascadia tsunami would overtop several at-risk coastal communities including Bay Center, Long Beach, Ocean Park, Ocean Shores, Raymond, and Westport. Many of these communities are popular with tourists year-round.

At-risk tribal communities include the Makah, Hoh, Quinault, Shoalwater, Quileute, and Lower Elwha Indian nations, each with small reservations in low-lying coastal areas. Most coastal Tribes need assistance as they have little to no infrastructure to support emergency planning and response.

The first tsunami wave will arrive in at-risk communities on the outer coast 30 to 60 minutes after a great Cascadia earthquake, and about 90 minutes later in at-risk communities along the Strait of Juan de Fuca. Significant flooding is expected before the first wave because the earthquake will lower the elevation of the coast about five feet.<sup>40</sup> Maximum flood depth and extent of flooding will depend on tide height at the time of tsunami arrival.

**Table 4. Projected Cascadia Tsunami Wave Heights For At-Risk Coastal Communities**

Ocean Park	29 Feet
Sunset Beach	20 Feet
Grayland	19 Feet
Long Beach	18 Feet
Westport, Ocean Shores	15 Feet
Quileute	13 Feet
Port Angeles	11 Feet
Neah Bay	10 Feet
Port Townsend	10 Feet
Aberdeen, Hoquiam	4 Feet

Note: Tsunami wave height may be larger depending upon local tide conditions. <sup>34, 35, 36, 37, 38, 39</sup>

Pacific County – Estimated at-risk residential population: 10,595 (50% of total)  
 – Estimated at-risk employee population: 5,096 (57% of total)

Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Shoalwater Indian Reservation	59	85%	138	100%
Raymond	1,098	37%	1,417	94%
South Bend	900	50%	630	44%
Long Beach	1,281	100%	1,259	100%
Ilwaco	433	46%	503	72%
Pacific County (remainder)	6,823	49%	1,149	36%

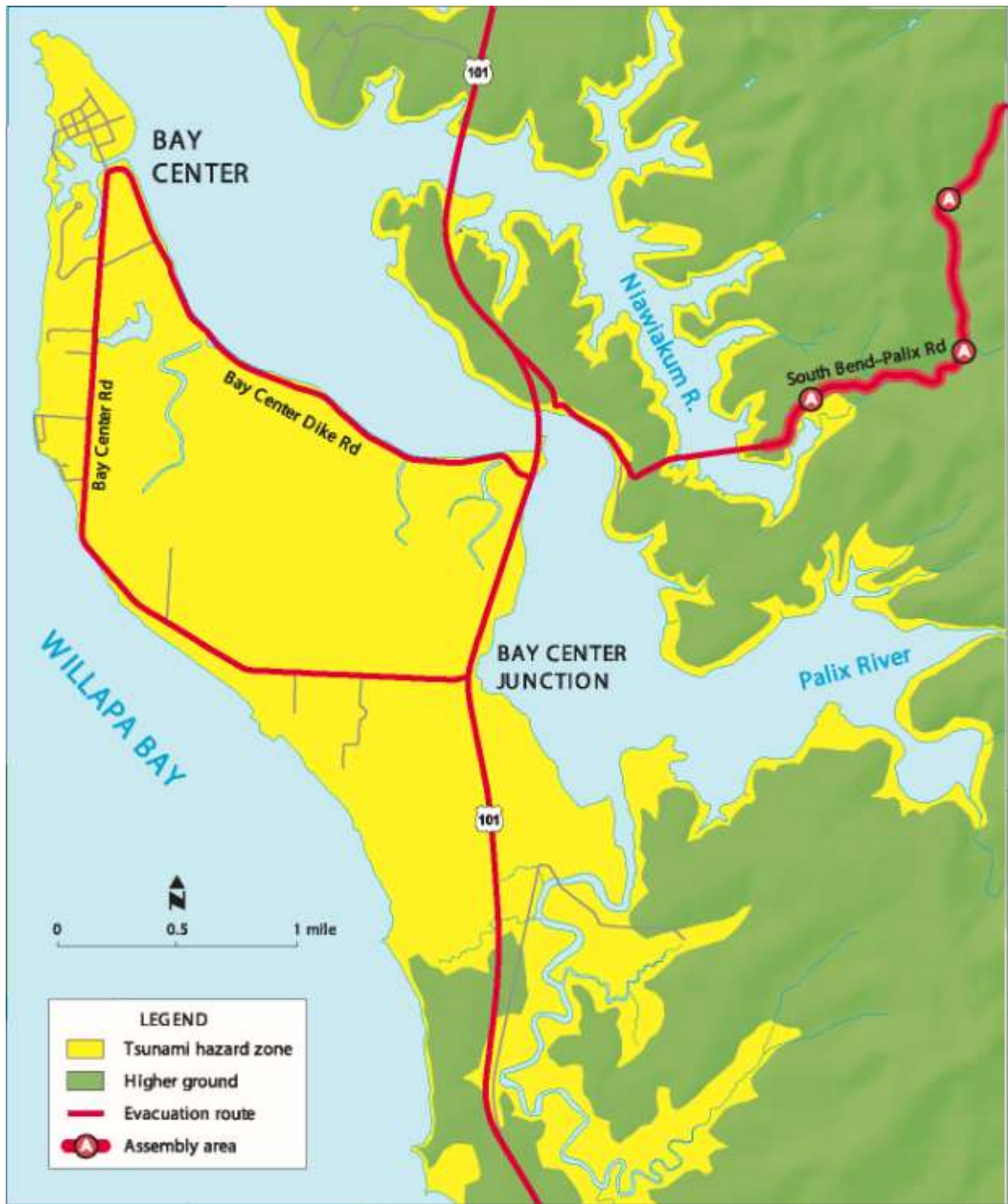
Communities with population at risk: Bay Center, Ilwaco, Long Beach, Ocean Park, Raymond, South Bend, Tokeland.

## Hazard Profile – Tsunami





## Hazard Profile – Tsunami



## Hazard Profile – Tsunami





## Hazard Profile – Tsunami

Grays Harbor County      – Estimated at-risk population: 28,447 (42% of total)  
    – Estimated at-risk employee population: 15,816 (62% of total)

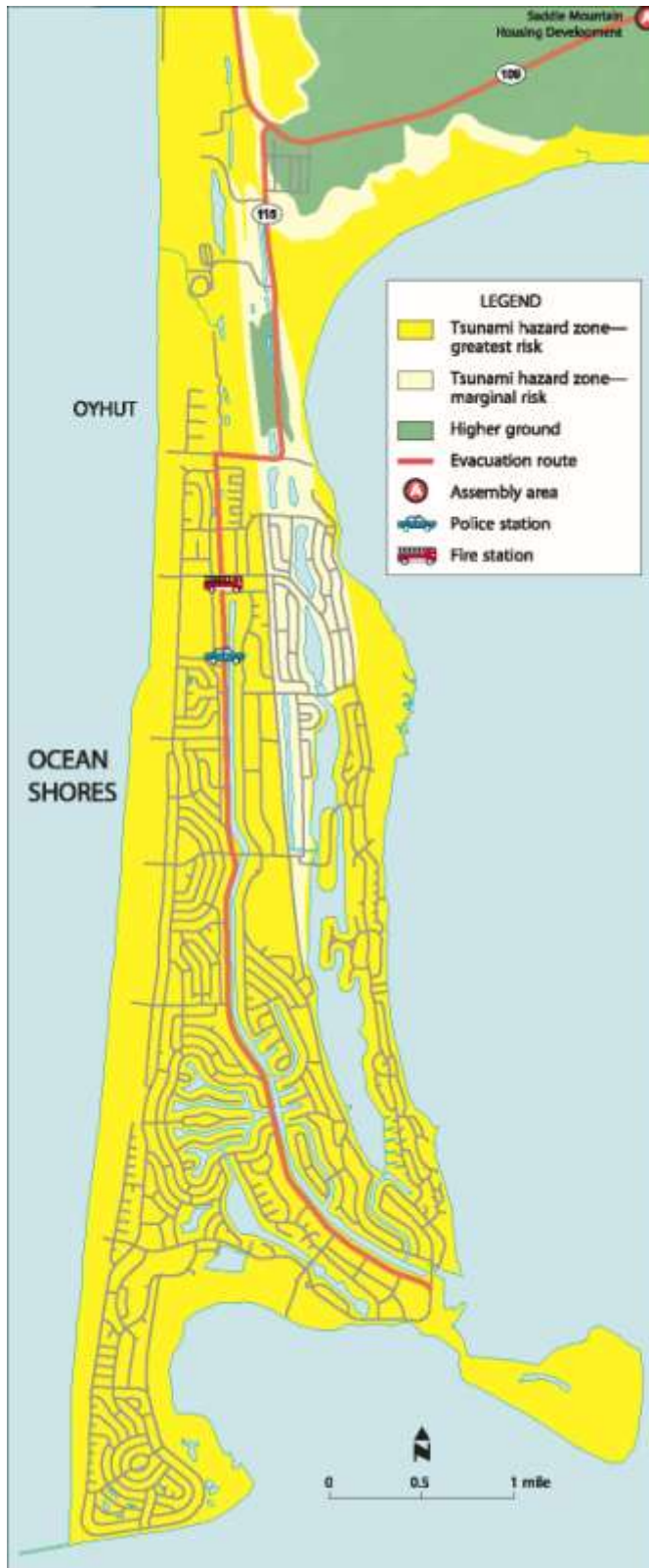
Communities with population at risk: Aberdeen, Cohasset Beach, Copalis Beach, Grayland, Hoquiam, Markham, Moclips, Ocean City, Ocean Shores, Oyhut-Hogans Corner, Taholah, Westport.

Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Quinault Indian Reservation	572	42%	449	65%
Ocean Shores	3,733	97%	1,603	98%
Hoquiam	5,756	63%	2,792	86%
Aberdeen	11,781	72%	7,488	81%
Cosmopolis	768	48%	229	88%
Montesano	28	1%	178	10%
Westport	1,900	89%	1,619	99%
Grays Harbor County (remainder)	3,957	13%	1,458	21%

## Hazard Profile – Tsunami



## Hazard Profile – Tsunami



## Hazard Profile – Tsunami





## Hazard Profile – Tsunami



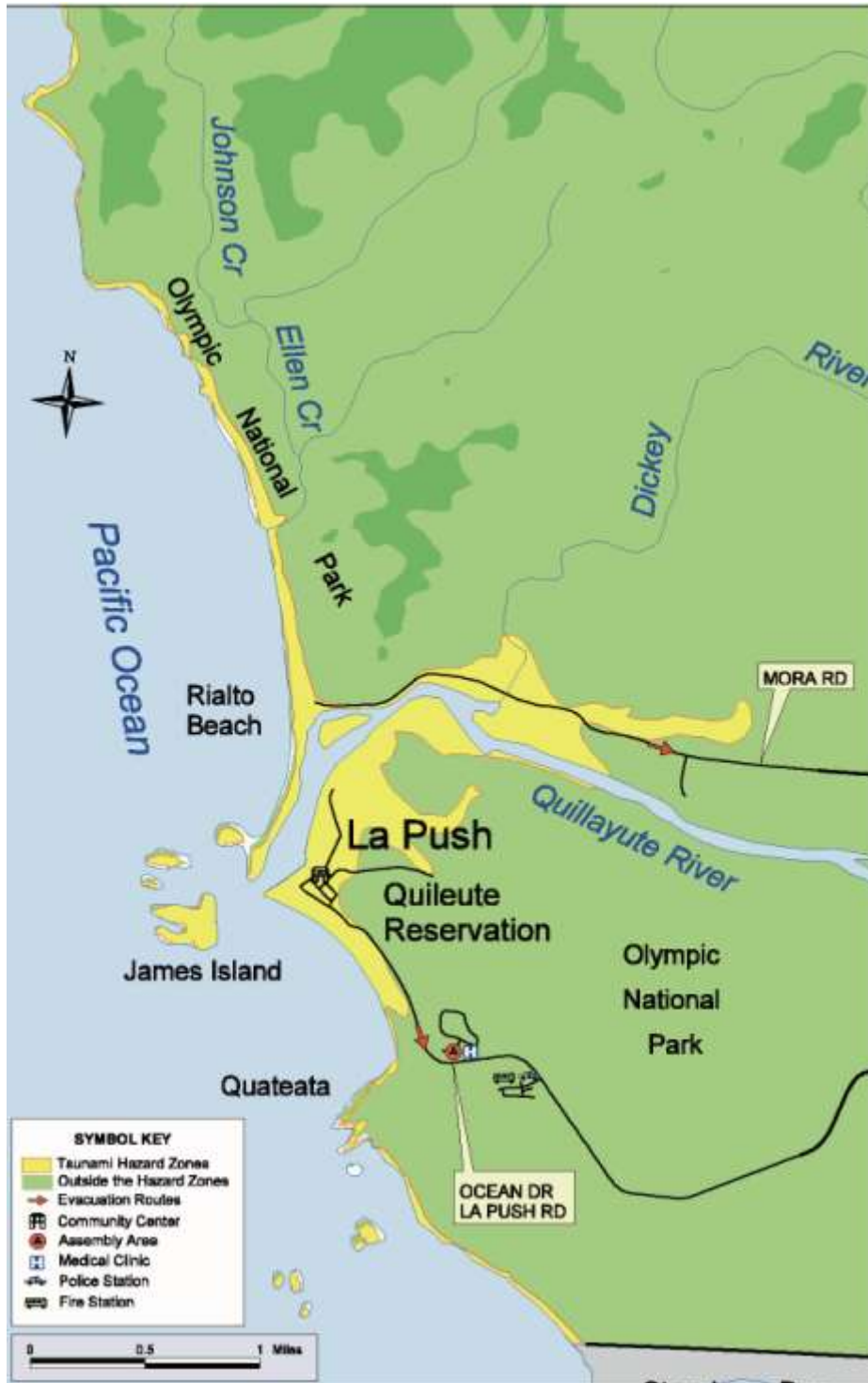
## Hazard Profile – Tsunami

Clallam County      – Estimated at-risk residential population: 2,239 (3% of total)  
                                  – Estimated at-risk employee population: 1,550 (5% of total)

Communities with population at risk: Clallam Bay, La Push, Neah Bay, Port Angeles, Sequim

Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Sequim	0	0%	15	0%
Port Angeles	143	1%	849	6%
Lower Elwa Indian Reservation	80	25%	4	10%
Makah Indian Reservation	802	59%	434	55%
Quileute Indian Reservation	54	15%	138	65%
Clallam County (remainder)	1,159	3%	110	1%

## Hazard Profile – Tsunami





## Hazard Profile – Tsunami



## Hazard Profile – Tsunami





## Hazard Profile – Tsunami



## Hazard Profile – Tsunami



## Hazard Profile – Tsunami

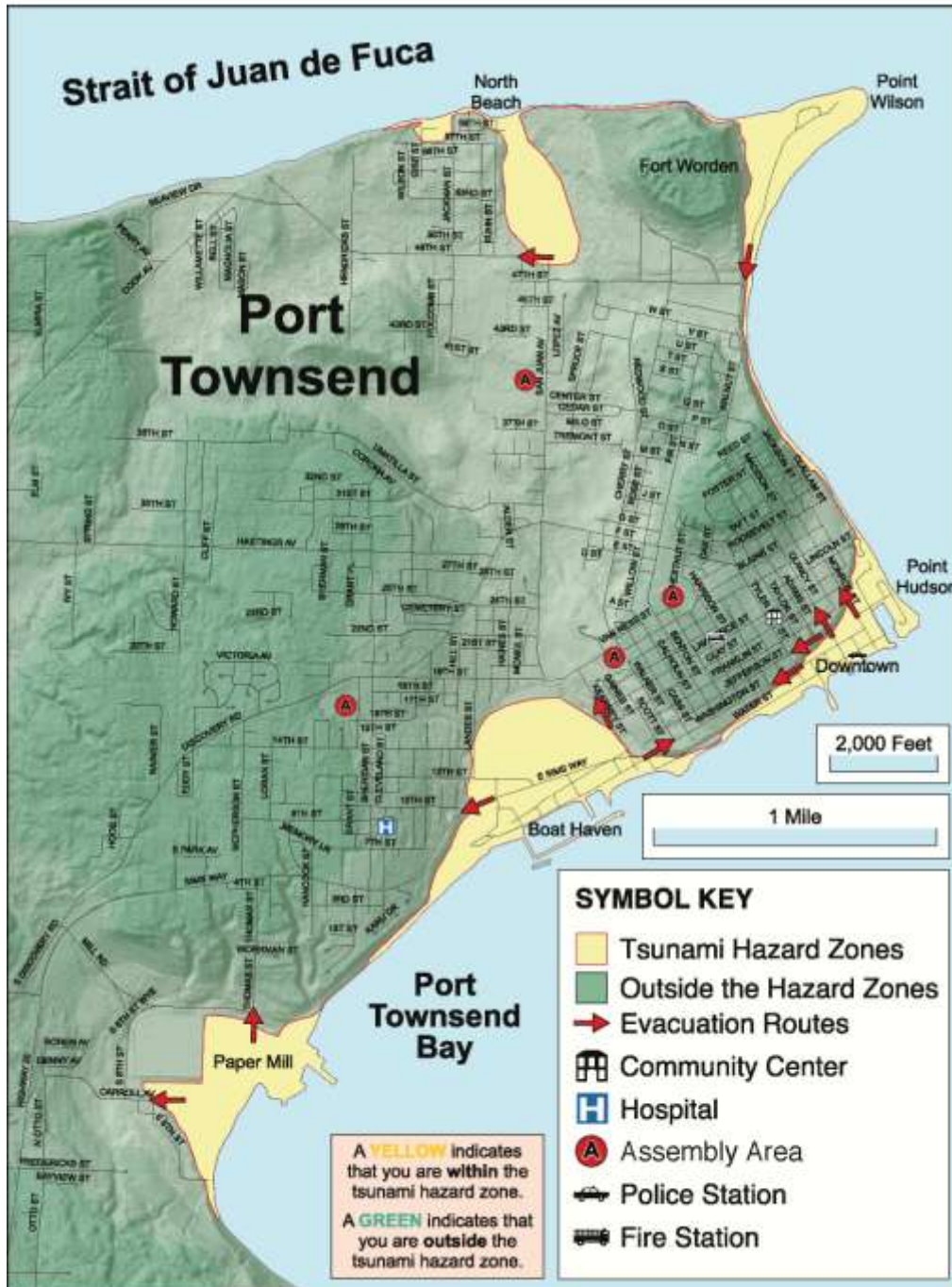
Jefferson County – Estimated at-risk residential population: 1,692 (7% of total)  
– Estimated at-risk employee population: 2,472 (23% of total)

Communities with population at risk: Marrowstone Island, Port Hadlock-Irondale, Port Townsend.

Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Hoh Indian Reservation	62	61%	0	0%
Port Townsend	424	5%	2,228	33%
Jefferson County (remainder)	1,157	7%	244	6%



## Hazard Profile – Tsunami

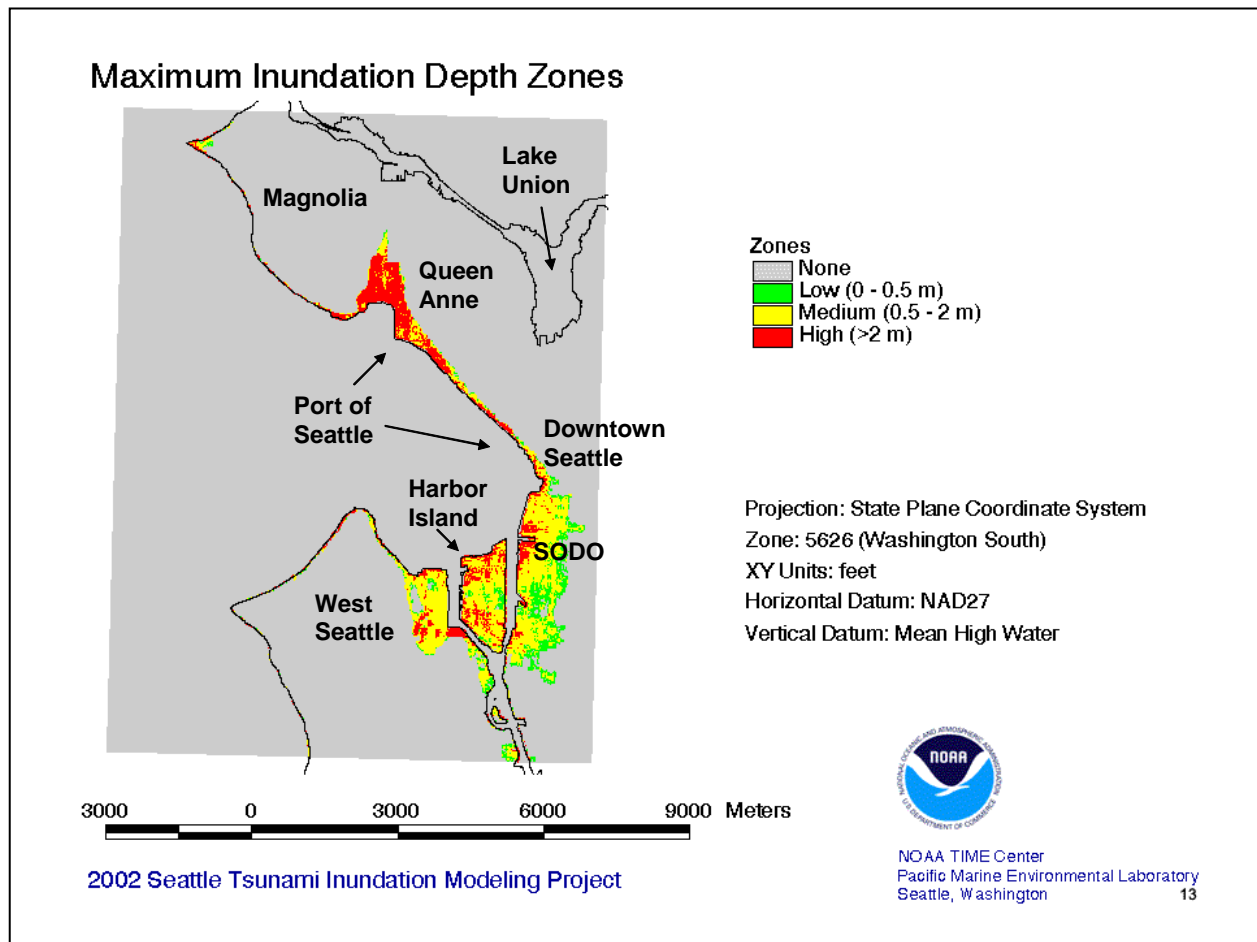


## Hazard Profile – Tsunami

Seattle<sup>41, 42</sup>

The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts has developed a tsunami inundation model for Elliott Bay in Seattle using as an initiating event a magnitude 7.3 earthquake on the Seattle Fault, which roughly parallels Interstate 90 through Seattle. The area modeled includes the portions of Seattle highlighted on the map below. The projected at-risk population of this area is 42,466 (from 2007 USGS, in development)

The tsunami is projected to hit the shoreline within two-and-a-half minutes of the earthquake and reach heights of up to 20 feet.





## Hazard Profile – Tsunami

### *Eastern Strait of Juan de Fuca*<sup>43</sup>

The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts has developed a tsunami inundation model for communities at the east end of the Strait of Juan de Fuca. The model uses an initiating event of a magnitude 9.1 earthquake on the Cascadia Subduction Zone off the Pacific Coast. The area modeled includes the highlighted areas on the maps below of the areas in Island, Skagit and Whatcom Counties.

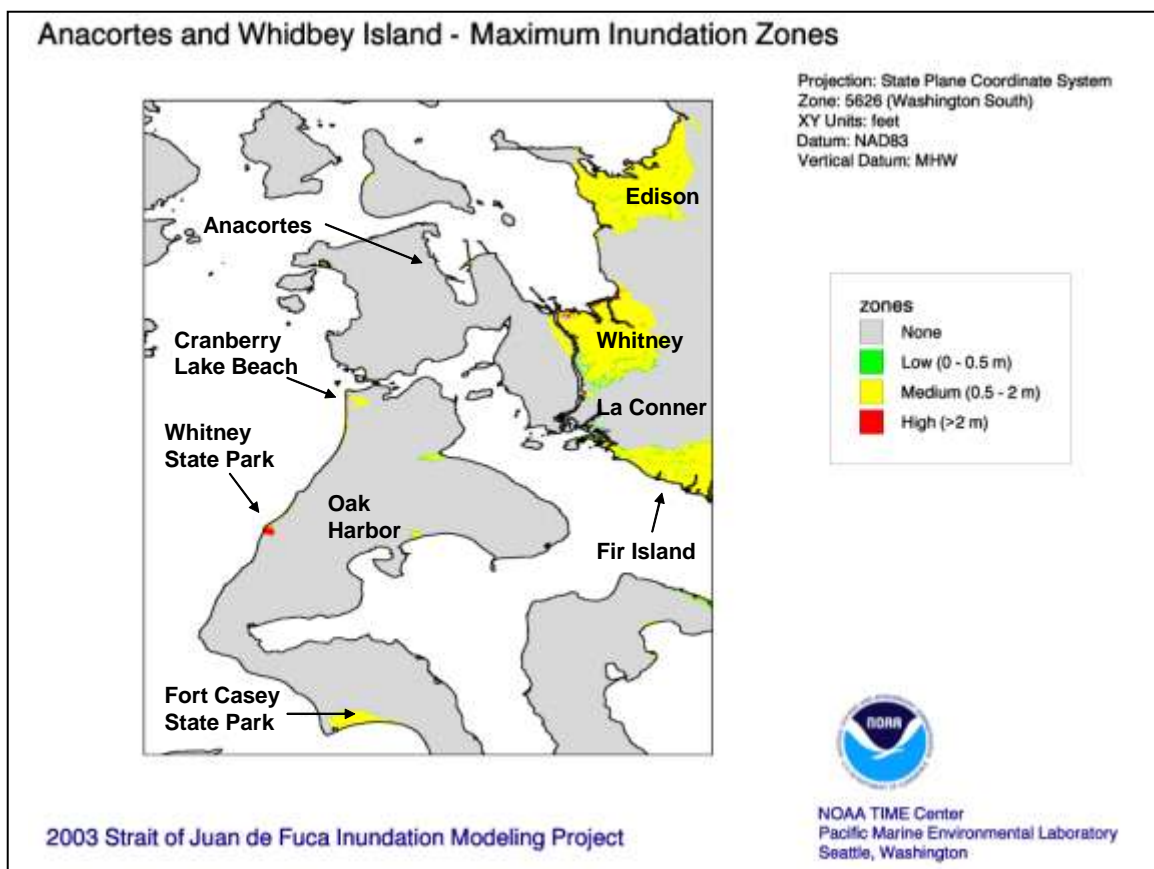
The first tsunami wave would hit the area two hours after the subduction zone earthquake. Maximum tsunami wave heights are projected to reach 11 feet in the Nooksack River delta near Bellingham, 8 feet at Whitney State Park on Whidbey Island, and 6.5 feet in the Anacortes area.

Skagit County – Projected at-risk population: 29,991.

Communities with population at risk: Edison, LaConnor, Fir Island, Whitney.

Island County – Projected at-risk population: 6,988.

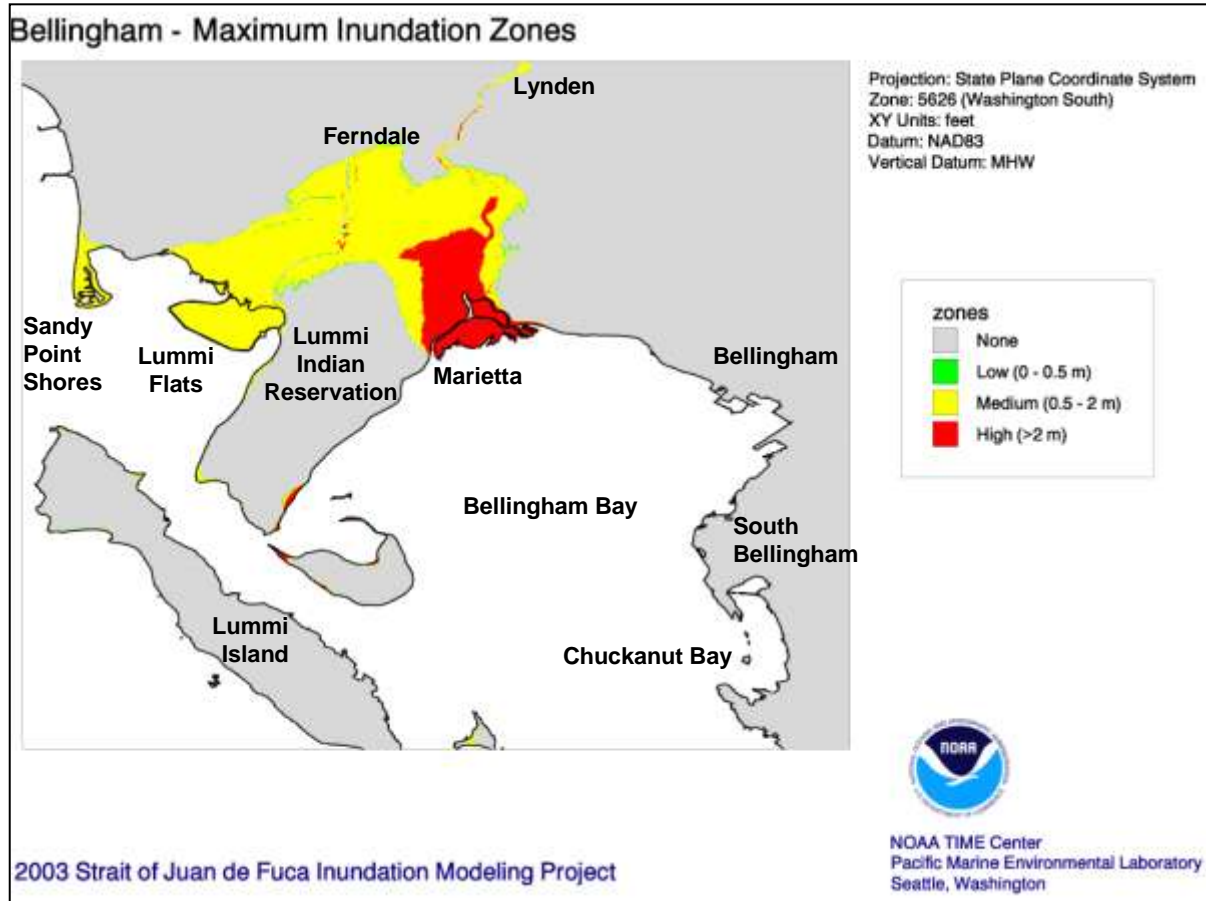
Communities with population at risk: Oak Harbor, Cranberry Lake Beach, Fort Casey State Park, Whitney State Park.



## Hazard Profile – Tsunami

Whatcom County – Projected at-risk population: 32,845.

Communities with population at risk: Ferndale, Lynden, Marietta, Lummi Indian Reservation, Lummi Flats, Sandy Point.



## Hazard Profile – Tsunami

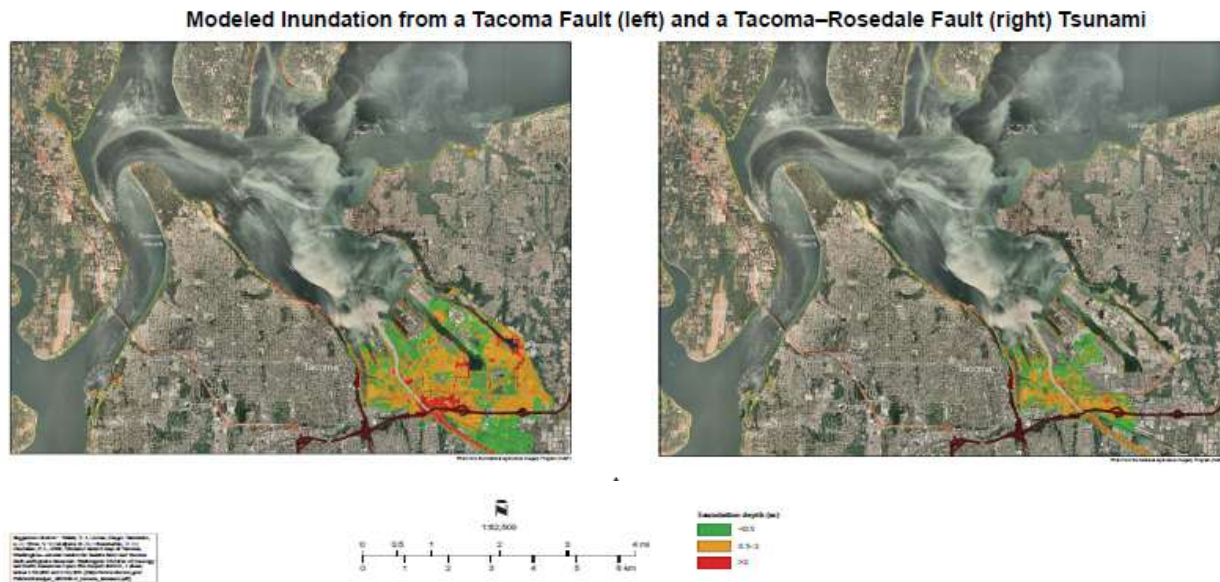
### *Tacoma*<sup>44</sup>

The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts has developed a tsunami inundation model for Tacoma using as an initiating event a magnitude 7.3 earthquake on the Seattle Fault, and two earthquakes on the Tacoma Fault. The area modeled includes the portions of the Tacoma area highlighted on the map below.

A tsunami from a Seattle Fault earthquake is projected to hit shorelines in Tacoma and Gig Harbor within 20 minutes of the earthquake and reach heights of up to 12 feet. A tsunami generated by a Tacoma Fault earthquake is projected to hit shorelines in Tacoma and Gig Harbor within 10 minutes of the earthquake and reach heights of up to 4 feet.

The projected at-risk population of this area is 55,900.

Communities potentially at risk: Gig Harbor, Tacoma, University Place.



(Excerpt from [http://www.dnr.wa.gov/Publications/ger\\_ofr2009-9\\_tsunami\\_hazard\\_tacoma.pdf](http://www.dnr.wa.gov/Publications/ger_ofr2009-9_tsunami_hazard_tacoma.pdf) exhibited below in full.



# Hazard Profile – Tsunami



## Tsunami Hazard Map of Tacoma, Washington: Model Results for Seattle Fault and Tacoma Fault Earthquake Tsunamis

by  
Timothy J. Walsh<sup>1</sup>, Diego Arcas<sup>2</sup>, Angie J. Venturato<sup>1</sup>, Vasily V. Titov<sup>1</sup>, Harold O. Mofjeld<sup>1</sup>, Chris C. Chamberlin<sup>1</sup>, and Frank I. Gonzalez<sup>1</sup>  
<sup>1</sup>Washington Division of Geology and Earth Resources, P.O. Box 47007, Olympia, WA 98504-47007; tim.walsh@dnr.wa.gov  
<sup>2</sup>NOAA Center for Tsunami Research, NOAA/PMEL-JUNISASO, 7500 Sand Point Way NE, Seattle, WA 98115



Modeled Inundation from a Seattle Fault Tsunami



Modeled Inundation from a Tacoma Fault (left) and a Tacoma–Rosedale Fault (right) Tsunami

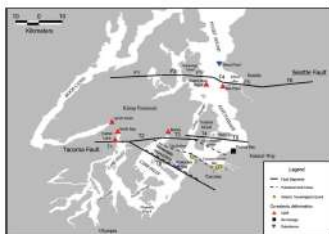


Figure 1. Location of Tacoma and surrounding areas. The map shows the city of Tacoma, Washington, and the surrounding area. The map is oriented with North at the top. The map shows the city of Tacoma, Washington, and the surrounding area. The map is oriented with North at the top.

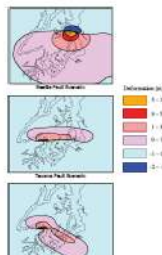


Figure 2. Location of Tacoma and surrounding areas. The map shows the city of Tacoma, Washington, and the surrounding area. The map is oriented with North at the top. The map shows the city of Tacoma, Washington, and the surrounding area. The map is oriented with North at the top.

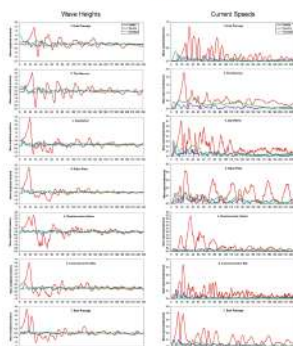


Figure 3. Time series of tsunami wave heights and currents at various stations. The figure consists of multiple subplots showing wave heights and currents over time for different stations.



Figure 4. Comparison of modeled inundation for the Seattle Fault and Tacoma Fault. The figure includes a map of Tacoma and surrounding areas, a legend for inundation depth, and a scale bar.

## Hazard Profile – Tsunami

### *Puget Sound – Everett to Olympia<sup>45</sup>*

Future projects planned by the National Tsunami Hazard Mitigation Program's National Center for Tsunami Research (formerly known as the Center for Tsunami Inundation Mapping Efforts) will develop tsunami inundation models for the following census designated and incorporated places (projected at-risk populations are for areas within one kilometer of the coastline, and subject to change).

King County (outside Seattle) – Projected at-risk population: 45,996.

Communities potentially at risk: Burien, Des Moines, Federal Way, Normandy Park, Vashon.

Kitsap County – Projected at-risk population: 61,731.

Communities potentially at risk: Bainbridge Island, Bremerton, Erlands Point, Manchester, Navy Yard City, Parkwood, Port Orchard, Poulsbo, Silverdale, Suquamish, and Tracyton.

Mason County – Projected at-risk population: 1,994.

Community potentially at risk: Allyn-Grapeview.

Snohomish County – Projected at-risk population: 55,661.

Communities potentially at risk: Edmonds, Everett, Marysville, Mukilteo, Picnic Point-North Lynnwood, Shaker Church, Stanwood, Tulalip Bay, Warm Beach, Weallup Lake, Woodway.

Thurston County – Projected at-risk population: 15,939.

Communities potentially at risk: Lacey, Olympia, Priest Point, Tumwater.

### **At-Risk State Facilities**

State Agency facilities identified as being at-risk to tsunami (see table, page 30) were determined using geo-spatial software to match their location to the tsunami inundation zones represented on maps on the previous pages.

## Hazard Profile – Tsunami

### State Agency Structures At Risk

### VULNERABILITY ASSESSMENT



#### Tsunami:

	# of Facilities	Total Original Cost	Avg. Original Cost	Total Square Feet	Average Sq. Ft.
<b>Owned:</b>	87	\$3,945,317	\$45,348	209,797	2,411
	# of Essential Facilities	Total Original Cost	Avg. Original Cost	Total Square Feet	Average Sq. Ft.
	4	\$102,579	\$410,319	12,886	3,221
	# of Facilities	Total Monthly Rent	Avg. Monthly Rent	Total Square Feet	Average Sq. Ft.
<b>Leased:</b>	40	\$355,919	\$8,897	290,868	7,217
	# of Essential Facilities	Total Monthly Rent	Avg. Monthly Rent	Total Square Feet	Average Sq. Ft.
	4	\$75,456	\$12,576	44,150	7,358

State owned structure within hazard zone:

Function of at-risk buildings: Included in the state facilities potentially at-risk to tsunami are the following:

- Eight public access points, Lake Whatcom Hatchery and Lake Aberdeen Hatchery operated by the Department of Fish and Wildlife.
- Ferry landings in Bremerton and Seattle.
- A variety of picnic, comfort, shelter and other facilities at 24 locations operated by the State Parks and recreation Commission.
- Seattle Armory and other facilities at Pier 91 in Seattle of the Military Department.
- State Patrol detachments in Hoquiam and Raymond.

One state highway considered an emphasis corridor because of its importance to movement of people and freight is potentially at-risk to tsunami as it traverses near vulnerable shorelines:

1. U.S. Highway 101

State critical facilities at risk within hazard zone:

Function of at-risk critical facilities: Included in the state facilities potentially at-risk to the direct and indirect impacts of tsunami are the following:

- Pump houses, chemical storage, and other facilities of Departments of Fish and Wildlife, Transportation, Ecology, and State Parks and Recreation Commission.
- Seattle Armory and other facilities at Pier 91 in Seattle of the Military Department.
- State Patrol detachments in Hoquiam and Raymond.

One state highway considered an emphasis corridor because of its importance to movement of people and freight is potentially at-risk to tsunami as it traverses near vulnerable shorelines:

1. U.S. Highway 101



## Hazard Profile – Tsunami

<sup>1</sup> *Tsunamis*, Washington Department of Natural Resources Division of Geology and Earth Resources, online fact sheet, <http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/tsuinfo.aspx>

<sup>2</sup> *NOAA and Tsunamis*, National Tsunami Hazard Mitigation Project, National Oceanic and Atmospheric Administration, online fact sheet, <http://www.publicaffairs.noaa.gov/grounders/tsunamis.html>, (March 26, 2003).

<sup>3</sup> *Tsunamis: Frequently Asked Questions*, National Tsunami Hazard Mitigation Project, National Oceanic and Atmospheric Administration, December 20, 2002, <http://nctr.pmel.noaa.gov/faq.php> (May 2, 2003).

<sup>4</sup> *EQ Facts and Lists: Largest Earthquake in the World*, U.S. Geological Survey Earthquake Hazards Program, [http://earthquake.usgs.gov/earthquakes/world/10\\_largest\\_world.php](http://earthquake.usgs.gov/earthquakes/world/10_largest_world.php) (September 22, 2005)

<sup>5</sup> From *Seismicity of the United States, 1568-1989 (Revised)*, Carl W. Stover and Jerry L. Coffman, U.S. Geological Survey Professional Paper 1527, U.S. Government Printing Office, Washington: 1993.

<sup>6</sup> *EQ Facts and Lists: Earthquakes with 1,000 or More Deaths from 1900*, U.S. Geological Survey Earthquake Hazards Program, [http://earthquake.usgs.gov/earthquakes/world/world\\_deaths.php](http://earthquake.usgs.gov/earthquakes/world/world_deaths.php), (September 22, 2005) .

<sup>7</sup> Ibid.

<sup>8</sup> *Earthquake in the News: Magnitude 9.0 – Sumatra-Andaman Islands Earthquake*, U.S. Geological Survey Earthquake Hazards Program, <<http://earthquake.usgs.gov/eqinthenews/2004/usslav/>>, (September 22, 2005).

<sup>9</sup> *The 26 December 2004 Indian Ocean Tsunami: Initial Findings from Sumatra*, U.S. Geological Survey, <<http://walrus.wr.usgs.gov/tsunami/sumatra05/index.html>>, (September 21, 2005)

<sup>10</sup> *Earthquake in the News: Magnitude 8.7 – Northern Sumatra, Indonesia*, U.S. Geological Survey Earthquake Hazards Program. (September 22, 2005).

<sup>11</sup> U.S. Dept. of Commerce. NOAA. Service Assessment: South Pacific Basin Tsunami – September 29-30, 2009. Accessed 21 June 2010. Available at: [http://www.weather.gov/os/assessments/pdfs/tsunami\\_%20south\\_pacific10.pdf](http://www.weather.gov/os/assessments/pdfs/tsunami_%20south_pacific10.pdf)

<sup>12</sup> *Frequently Asked Questions About Tsunamis*, International Tsunami Information Center, National Oceanic and Atmospheric Administration, <http://www.weather.gov/ptwc/faq.php>, (November 4, 2002).

<sup>13</sup> Current approximate recurrence rate of M9.0 Cascadia Subduction Zone provided by Arthur D. Frankel, U.S. Geological Survey, in an oral presentation at the *Workshop on Geologic Research in the Seattle Area*, University of Washington, October 20, 2003.

<sup>14</sup> *Division of Geology and Earth Resources News*, Washington Department of Natural Resources, Division of Geology and Earth Resources, Vol. 2, No. 1, Spring 2005.

<sup>15</sup> Timothy J. Walsh et al., *Tsunami Hazard Map of the Southern Washington Coast: Modeled Tsunami Inundation from a Cascadia Subduction Zone Earthquake*, Washington Department of Natural Resources Division of Geology and Earth Resources, Geologic Map GM-49, October 2000.

<sup>16</sup> Thomas J. Sokolowski, *The Great Alaskan Earthquake and Tsunamis of 1964*, West Coast and Alaska Tsunami Warning Center. (March 25, 2003).

<sup>17</sup> *April 13, 1949 Puget Sound Tsunami – Salmon Beach Narrative*, West Coast and Alaska Tsunami Warning Center, National Oceanic and Atmospheric Administration. (March 26, 2003).

<sup>18</sup> *Tsunamis Affecting the West Coast of the United States 1806 – 1992*, National Geophysical Data Center Key to Geophysical Records Documentation No. 29, National Oceanic and Atmospheric Administration, December 1993.

## Hazard Profile – Tsunami

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- <sup>19</sup> Walsh, Timothy J., et al. *Tsunami Hazard Map of the Southern Washington Coast*. (2000). Washington State Department of Natural Resources.
- <sup>20</sup> High Shipman, *The Fall of Camano Head: A Snohomish Account of a Large Landslide and Tsunami in Possession Sound During the Early 1800s*, TsulInfo Alert, Volume 3, No. 6, December 2001.
- <sup>21</sup> *Tsunamis Affecting the West Coast of the United States 1806 – 1992*, National Geophysical Data Center Key to Geophysical Records Documentation No. 29, National Oceanic and Atmospheric Administration, December 1993.
- <sup>22</sup> Don J. Miller, *Giant Waves in Lituya Bay Alaska – Shorter Contributions to General Geology*, U.S. Department of the Interior, Geological Survey Professional Paper 354-C, 1960.
- <sup>23</sup> Lee Walkling, *Infrequently Asked Questions*, TsulInfo Alert, Volume 1, No. 2, February 1999.
- <sup>24</sup> Oral communication from Timothy J. Walsh, Chief Geologist, Washington Department of Natural Resources, May 1, 2003.
- <sup>25</sup> *What Causes Damage*, University of Washington, Pacific Northwest Seismograph Network fact sheet, <[http://www.geophys.washington.edu/SEIS/PNSN/INFO\\_GENERAL/NQT/what\\_causes\\_damage.html](http://www.geophys.washington.edu/SEIS/PNSN/INFO_GENERAL/NQT/what_causes_damage.html)>, (August 11, 2003).
- <sup>26</sup> A. Barberopoulou et al., *Local Amplification of Seismic Waves from the M7.9 Alaska Earthquake and Damaging Seiches in Lake Union, Seattle, Washington*, Paper No. 263-9, Geological Society of America, Vol. 35, No. 6, September 2003, p. 646.
- <sup>27</sup> Aberdeen Daily World, March 31, 1964.
- <sup>28</sup> National Tsunami Hazard Mitigation Program, National Oceanic and Atmospheric Administration Pacific Marine Environmental Laboratory, <<http://www.pmel.noaa.gov/tsunami/time/wa/population/index.shtml>>, (March 26, 2003).
- <sup>29</sup> V.V. Titov et al., 2003. NOAA TIME Seattle Tsunami Mapping Project: Procedures, data sources, and products, NOAA Technical Memo OAR PMEL-124 (in preparation).
- <sup>30</sup> General information and population figures from *TIME Workshop – At-Risk Population*, NOAA National Tsunami Hazard Mitigation Program Center for Tsunami Inundation Mapping Efforts. (March 26, 2003).
- <sup>31</sup> Timothy J. Walsh et al., *Tsunami Hazard Map of the Port Angeles, Washington, Area*, Washington Department of Natural Resources Division of Geology and Earth Resources, Open File Report 2002-1, August 2002.
- <sup>32</sup> Timothy J. Walsh et al., *Tsunami Hazard Map of the Port Townsend, Washington, Area*, Washington Department of Natural Resources Division of Geology and Earth Resources, Open File Report 2002-2, August 2002.
- <sup>33</sup> Wood, N., and Soulard, C., 2008, Variations in community exposure and sensitivity to tsunami hazards on the open-ocean and Strait of Juan de Fuca coasts of Washington: U.S. Geological Survey Scientific Investigations Report 2008-5004, 34 p. [<http://pubs.usgs.gov/sir/2008/5004/>]
- <sup>34</sup> *Tsunami Hazard Map of the Southern Washington Coast: Modeled Tsunami Inundation from a Cascadia Subduction Zone Earthquake*, Timothy J. Walsh, et.al., Washington Department of Natural Resources, Geologic Map GM-49, October 2000.
- <sup>35</sup> *Tsunami Inundation Map of the Neah Bay, Washington Area*, Timothy J. Walsh, et.al., Washington Department of Natural Resources, OFR 2003-2, January 2003.
- <sup>36</sup> *Tsunami Inundation Map of the Quileute, Washington Area*, Timothy J. Walsh, et.al., Washington Department of Natural Resources, OFR 2003-1, January 2003.
- <sup>37</sup> *Tsunami Inundation Map of the Port Townsend, Washington Area*, Timothy J. Walsh, et.al., Washington Department of Natural Resources, OFR 2002-2, August 2002.
- <sup>38</sup> *Tsunami Inundation Map of the Port Angeles, Washington Area*, Timothy J. Walsh, et.al., Washington Department of Natural Resources, OFR 2002-1, August 2002.

## Hazard Profile – Tsunami

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<sup>39</sup> A.J. Venturato, et.al., *NOAA TIME Eastern Strait of Juan de Fuca, Washington, Mapping Project: Procedures, Data Sources, and Products*, NOAA Technical Memorandum OAR PMEL-127, September 2004

<sup>40</sup> *Cascadia Subduction Zone tsunamis – Hazard Mapping at Yaquina Bay, Oregon*, G.R. Priest, et.al., Oregon Department of Geology and Mineral Industries, Open File Report O-97-34, 1997.

<sup>41</sup> *TIME Workshop – At-Risk Population*, NOAA National Tsunami Hazard Mitigation Program Center for Tsunami Inundation Mapping Efforts, <[http://www.pmel.noaa.gov/tsunami/time/wa/population/wa\\_2.shtml](http://www.pmel.noaa.gov/tsunami/time/wa/population/wa_2.shtml)>, (March 26, 2003).

<sup>42</sup> V.V. Titov, et.al., *NOAA TIME Seattle Mapping Project: Procedures, Data Sources, and Products*, NOAA Technical Memorandum OAR PMEL-124, September 2003

<sup>43</sup> Product Reports, 2003 Eastern Strait of Juan de Fuca Inundation Modeling Project, NOAA National Tsunami Hazard Mitigation Program Center for Tsunami Inundation Mapping Efforts, July 2003.

<sup>44</sup> Product Report, Inundation Modeling Projects for Tacoma, Washington, NOAA National Center for Tsunami Research, Pacific Marine Environmental Laboratory, January 2006.

<sup>45</sup> *TIME Workshop – At-Risk Population*, NOAA National Tsunami Hazard Mitigation Program Center for Tsunami Inundation Mapping Efforts, < [http://www.pmel.noaa.gov/tsunami/time/wa/population/wa\\_3.shtml](http://www.pmel.noaa.gov/tsunami/time/wa/population/wa_3.shtml)>, (March 26, 2003).